The effect of polyurethane encapsulant on the response of PVDF hydrophones in the frequency range from 30 kHz to 100 kHz.

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ABSTRACT

PVDF has many properties that make it attractive for use as an underwater sensor and a number of groups have reported on such work. In order to use such sensors it is necessary to encapsulate the piezoelectric material in polyurethane for waterproofing. In terms of ceramic sensors the ceramic itself acts as the acoustic pickup and it is desirable to have a polyurethane encapsulant with an acoustic impedance close to that of water. PVDF however has an acoustic impedance similar to water and consequently the coupling of sound into the PVDF is via the encapsulant or the supporting substrate. In order to fully understand and model the PVDF sensor performance it is therefore necessary to have a detailed knowledge of the physical properties of the polyurethane encapsulant. However, in our experience, obtaining such information for various commercially available polyurethanes has proven very difficult. This paper reports on the fabrication and characterisation of thin film and coaxial PVDF encapsulated in a Scorpion polyurethane. The effect of the polyurethane on the sensitivity and directivity of various sensors will be discussed.

INTRODUCTION

Polyvinylidene fluoride (PVDF) has been used by a number of researchers for hydrophone applications. For example large area hydrophone arrays have been reported by Henriquez (Henriquez 1985), bimorph hydrophones by Josserand (Josserand 1985) and composite arrays by Lau (Lau 2002). Kharat et al gives a good overview of some of these applications in his paper (Kharat 2007) together with some basic design considerations.The main objective of our work with PVDF is to fabricate a 3D vector hydrophone for underwater applications. While initial attempts have been promising (Killeen 2009, Killeen 2012) the need has become clear to have a better understanding of the physical mechanism involved in the conversion of the pressure signal into a voltage. More specifically we need to understand the effects of the polyurethane encapsulant on the transfer of energy into the piezoelectric film. In order to successfully construct a vector probe using PVDF it will be necessary to be able to accurately model the sound field inside the sensor. While Moffett et al (Moffett 1986) sucessfully modelled the far field directionality of his sensor at f= 100 kHz using a rigid baffle this gives no information on what is actually happening inside the sensor. The aim of this work is to try and use a finite element model [PAFEC] (PAC^{SYS}) using the physical properties of the encapsulant and PVDF film, to fit to the observed far field directionality of the sensor. Due to limitations in manufacturer specifications it has been necessary to directly measure the compressional sound speed of the polyurethane using the sensors themselves.

SENSOR FABRICATION

Four PVDF sensors were constructed and tested in this report. All four were encapsulated in two-pack Scorpion Polyurethane (Scorpion). The PVDF films and coaxial cable used for the first three sensors were purchased from Measurement Specialties Inc (Measurement 1999). The piezo cable has the appearance of normal coaxial cable but there is a layer of PVDF (spiral) between the inner conductor and outer shield. The cable is surrounded by a polyurethane outer layer. The PVDF film for sensor four was purchased from Airmar Technologies Corporation (Airmar 1999). The four sensors are listed below,

SDT1 Shielded sensor (Rectangle). This sensor consists of a 28 · m thick film of PVDF that has been doubled over to give an effective thickness (t) of 56 μm. In doing so the thick film silver electrodes act as a shield and give significant reduction in sensor noise. The length (l) and width (w) of the PVDF film is 30mm and 13 mm respectively. The film was encapsulated at the centre of a rectangle of polyurethane with dimensions, L = 37 mm, W = 21 mm and T = 6.5 mm

SDT1 Shielded sensor (Cylinder). This used the same piezo film as in sensor 1 except it was encapsulated at the centre of a cylinder of polyurethane of diameter 40 mm and length 90 mm.

Piezo polymer coaxial cable. Five pieces of PVDF cable were encapsulated inside a cylinder of polyurethane of radius 40 mm and length 210 mm. The length of each PVDF sensor was 100 mm with an external diameter of 3 mm. A supporting framework consisting of plastic ends and carbon fibre rods was used to hold the PVDF sensors in place during fabrication. The distance between the central sensor and the outside sensors was 15mm.

AIRMAR PiezofLEX polymer (Rectangle). The dimensions of the piezo film was made to be the same as that reported in the work of Moffet (Moffett 1986) with l = w = 19 mm. The film thickness is 515 µm which is a factor of ten greater than the SDT1 film. The film was encapsulated in a rectangle of polyurethane with dimension L = 47 mm, W = 25 mm and T = 6.5 mm.

RESULTS.

All sensors were characterised in a tank using a calibrated Reson 4014-5 hydrophone. An ITC 1042 hydrophone was used as a transmitter located at the centre of the tank. The Reson hydrophone and test sensor were located either side of the 1042 at a distance of 450mm. The water depth was 1000 mm and the tank diameter 1800 mm. A burst of ten cycles of constant frequency sine wave was transmitted every second. In order to avoid surface and tank reflections the lower frequency was restricted to 30 kHz. The upper frequency was chosen as 100 kHz which was close to the upper useable frequency of the transmitting hydrophone. The angular dependence of the sensors was measured by rotating the sensor every 10 degrees and measuring its voltage output. In addition to this the response of the sensors was measured orthogonal to the face of the PVDF film with a frequency increment of 2 kHz for the frequencies of interest (30 kHz< f < 100 kHz).

The polyurethane used for this work was a Scorpion two pack polyurethane (SOL-RES 01). It was reported to have a Shore Hardness (A) of 80-90 and a density of 990 kgm^{-3}. No other parameters were provided with the documentation. It was therefore necessary to measure other parameters to support our FEM in this area. Estimation of the sound speed of the polyurethane was done using coaxial sensor 3. By aligning three of the sensors parallel with the sound source it was possible to directly measure the arrival time of the pulse across the three sensors which were equally spaced at 15 mm. For the entire frequency range 30 kHz< f < 100 kHz the sound speed was measured as 1630 ms^{-1}. This corresponds to an acoustic impedance of 1.52 $x10^6$ Kg m^{-2} s^{-1} which is very close to that of water. It is interesting to compare this to the acoustic impedance of the SDT1 PVDF = 2.7 $x10^6$ Kg m^{-2} and the Airmar PVDF = $1.2x10^6$ Kg m^{-2} s^{-1}. A list of physical properties of the various materials used is given in table 1.

Table 1: Physical parameters for the various materials used.

	ρ(kgm⁻³)	*Z(kgm⁻²s⁻¹)*	*c (ms⁻¹)*	*T (µm)*
SDT1	$1.78x10^3$	$2.7x10^6$	$1.517x10^3$	56
AIRMAR	$1.47x10^3$	$1.2x10^6$	$8.16x10^2$	515
MOFFETT	$1.46x10^3$	$1.4x10^6$	$9.75x10^2$	330
CABLE	$1.89x10^3$	$4.0x10^6$	$2.116x10^3$	?
POLY	$9.9x10^2$	$1.52x10^6$	$1.63x10^3$	-
WATER	$1.0x10^3$	$1.5x10^6$	$1.5x10^3$	-

Figure 1 shows the frequency dependence of the open circuit sensitivity (M_o), orthogonal to the face of the film, for the Airmar hydrophone (sensor #4), the SDT1 hydrophone (sensor#1), the PVDF coaxial cable hydrophone (sensor #3) and the Moffett hydrophone for the frequency range 30 kHz< f < 100 kHz. The M_o of the Airmar and Moffett hydrophones are very similar as would be expected from comparison of their physical parameters in table 1. The thinner SDT1 hydrophone has a sensitivity of ~12dB less than the Airmar and Moffett sensors over the entire frequency range and the coaxial PVDF cable is approximately 3 dB below the SDT1.

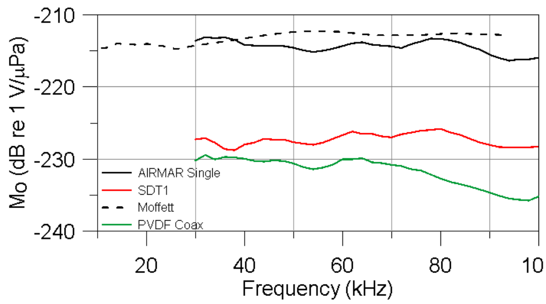

Figure 1. Frequency dependence of the free field sensitivity M_o orthogonal to the face of the film.

As discussed by Moffett, for higher frequencies where the film width is greater than a wavelength the film operates in thickness mode. In this case the open circuit voltage per unit free field pressure is given by,

$$m_o = \frac{h_{33} l}{\rho_o c_o^2} r \frac{1}{\sqrt{1+(r^2-1)cos^2\psi}} \frac{sin\psi}{\psi} \quad (1)$$

where

$$r = \frac{\rho_o c_o}{\rho c} \quad (2)$$

$$\psi = \frac{\omega l}{2c_o} \quad (3)$$

h_{33} is the thickness expansion piezoelectric constant, $\omega=2\pi f$ and l is the thickness of the film. $\rho_o c_o$ is the acoustic impedance of the PVDF film and ρc is the acoustic impedance of water. The open circuit sensitivity can then be obtained from M_o using,

$$M_o = 20log|m_o| - 120 \quad (4)$$

For the PVDF film used by Moffett h_{33} was unknown and they varied this parameter to give a best fit for the frequency variation of M_o . This was found to be h_{33} = 2.0 x 10^8 Vm^{-1} (Moffett 1986). Interestingly, using their data and equations (1) and (4) we obtained best agreement with h_{33} = 1.0 x 10^8 Vm^{-1}. Figure 2 show the measured sensitivity of the Airmar sensor together with the sensitivity obtained using equations 1 and 4 (blue dotted line). The value of h_{33} was estimated using,

$$h_{33} = g_{33}c_{33}^D \quad (5)$$

Where C_{33}^D is the stiffness constant and g_{33} is the piezoelectric stress constant. g_{33} and c_{33} were calculated from the dielectric, elastic and piezoelectric parameters reported by Roh et al (Roh 2002). In his paper he characterised a film that appears to be identical to the Airmar film used in this report. From this information the thickness expansion piezoelectric constant h_{33} was estimated to be 4.11 x 10^8 Vm^{-1}. This value was used in equation 1 to calculate the sensitivity curve shown in Figure 2 (blue dotted). As can be seen there is a difference of approximately 21 dB between the theory and the data.

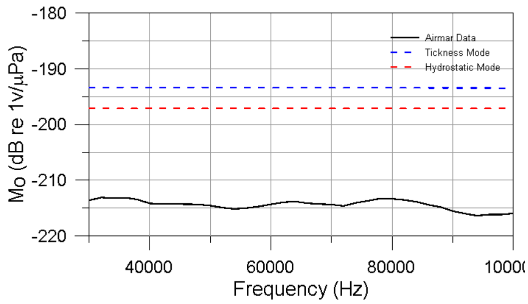

Figure 2. Measured sensitivities of the Airmar sensor together with the sensitivity values obtained using equations 1 and 5 (dotted lines).

This is probably not that suprising since the wavelengths in question are comparable to the film width which violates the initial assumption for using thickness mode operation. At 30 kHz, λ = 5cm and at 100 kH, λ = 1.5 cm. It is not until 80 kHz that the wavelength is equal to the film dimension. The validity of using the above theory to fit the data at these frequencies is therefore questionable and the agreement obtained by Moffett (Moffett 1986) was probably due to the fact that h_{33} was used as the fitting parameter.

In the case of lower frequencies where the wavelength becomes significantly larger than the film dimension then it is more reasonable to assume that the film operates in hydrostatic mode. In this case,

$$m_o = g_h t \quad (5)$$

Where g_h is the volume expansion piezoelectric constant given by,

$$g_h = g_{31} + g_{32} + g_{33} \quad (6)$$

Table 2 shows these values for the Airmar and SDT1 piezoelectric materials together with the calculated sensitivities using equations 5 and 6,

For the Airmar sensor M_o was estimated to be -197 db re 1V/µPa. This is shown by the red dotted line in Figure 2. As can be seen the calculated sensitivity is still 17 dB larger than that measured. This is surprising since the hydrostatic mode should give the minimum sensitivity of the film and as a result it would be expected to lower than the data. It should however be noted that the validity of using equation 5 is that wavelengths are significantly larger than the film dimension which in our frequency range is not the case.

To investigate possible attenuation effects of the polyurethane a comparison was made between the two SDT1 films encapsulated in rectangular and cylindrical polyurethane. Figure 3 shows the frequency dependence of the sensitivity of the two SDT1 sensors (#1 and #2) at normal incidence. As can be seen the cylindrical sensor is ~3-4 dB more sensitive over the entire frequency range. This is surprising considering that for the cylindrical sensor the thickness of the polyurethane between the face of the sensor and the film is approximately five times that of the rectangular sensor.

Table 2: Piezoelectric constants used for calculating the hydrostatic sensitivity of the Airmar and SDT1 films.

	g_{31} (VmN^{-1})	g_{32} (VmN^{-1})	g_{33} (VmN^{-1})	g_{3h} (VmN^{-1})	M_o (dBre1V/µPa)
AIRMAR	.21	.03	-0.5	-0.27	-197
SDT1	.216	0.003	-0.33	-0.11	-224

Figure 4 shows a contour plot of the angular variation of M_o for both SDT1 sensors. The overall similarity of the two plots suggests that the polyurethane is having little effect on the sensor directivity and that the variations observed are due the films themselves. The narrower minima observed in the cylindrical sensor at θ~60° and 110° may possibly be due to small misalignments in the film which might have occurred during fabrication.

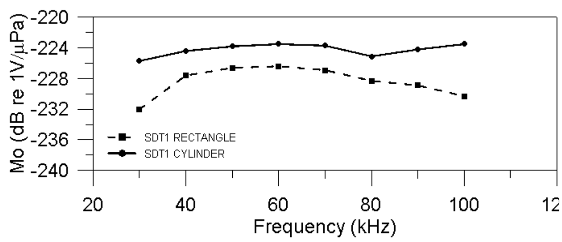

Figure 3. Frequency dependence of the orthogonal sensitivities of the rectangular and cylindrical SDT1 sensors

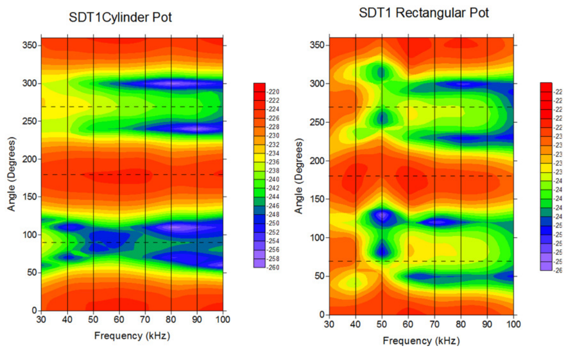

Figure 4. Contour plot of the angular variation of M_o for cylindrical and rectangular SDT1 sensors

It is common to model the angular variation of sensitivity plots in terms of an aperture function and Moffett et al found good agreement at f= 100 kHz (Moffett 1986). It can be shown that for a rectangular piston with side lengths w and l, the directivity amplitude function (DAF) Γ(θ,ϕ) is given by (Urban 2002),

$$\Gamma(\theta,\phi) = \frac{sin\left[\frac{w\pi}{\lambda}sin\theta cos\phi\right]}{\frac{w\pi}{\lambda}sin\theta cos\phi}\frac{sin\left[\frac{l\pi}{\lambda}sin\theta cos\phi\right]}{\frac{l\pi}{\lambda}sin\theta cos\phi} \quad (7)$$

Where θ is the angle in the horizontal plane and ϕ is the angle in the vertical plane. For the results discussed in this paper ϕ = 90^o and equation 5 reduces to,

$$\Gamma(\theta,\phi) = \frac{sin\left[\frac{l\pi}{\lambda}sin\theta cos\phi\right]}{\frac{l\pi}{\lambda}sin\theta cos\phi} \quad (6)$$

Equation 6 was used by Moffett to give good agreement with his data at f= 100 kHz (Moffett 1986). Figure 5 shows the normalized directivity plots for our Airmar film (black) for 30 kHz< f < 100 kHz. The red curve is the calculated values using equation 6. As was seen by Moffett there is reasonable agreement at f = 100 kHz. There is also reasonable agreement at the lower frequencies (f= 30 kHz and 40 kHz) but for the middle frequencies the agreement is bad. It should be noted that the positions of the minima at θ~ 45, 135, 225, 315^o are virtually independent of frequency which indicates that the directivity patterns observed are not due to the aperture function given by equation 6. Figure 6 shows a similar set of results for the SDT1 sensor. In this case l= 30 mm. Good agreement between the model and experiment was only found at f= 60 kHz and 70 kHz. Minima in the measured directivity patterns were observed at the same position as those shown in figure 6 and were again independent of frequency.

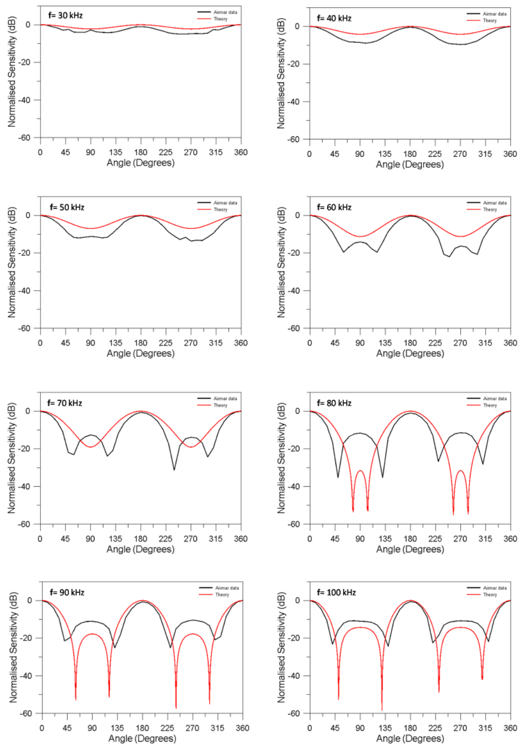

Figure 5. Normalized directivity plots for the Airmar sensor (black) and theoretical directivity using equation 6.

Figure 7 shows the results for the directivity for the same Airmar sensor shown in figure 5 except the theoretical results were obtained using PAFEC. Physical and piezoelectric properties of the Airmar PVDF were derived from those found in the literature (Roh 2002). For the polyurethane, the parameters in Table 3 were assumed. As can be seen there is a better agreement over the entire frequency range compared to the results shown in figure 5 but there are still some large deviations at lower frequencies. It should be noted however that this is our initial attempt at modelling the data and improvements are likely to happen when an optimisation routine is used to fit the parameters, or they can be measured.

Table 3: Polyurethane parameters used in FEM modelling.

Polyurethane Parameter	*Value*
Sound Speed	1650 ms^{-1}
Sound Attenuation	8 $dB\lambda^{-1}$
Shear Speed	75 ms^{-1}
Shear Attenuation	0.3 $dB\lambda^{-1}$
Density	990 kgm^{-3}

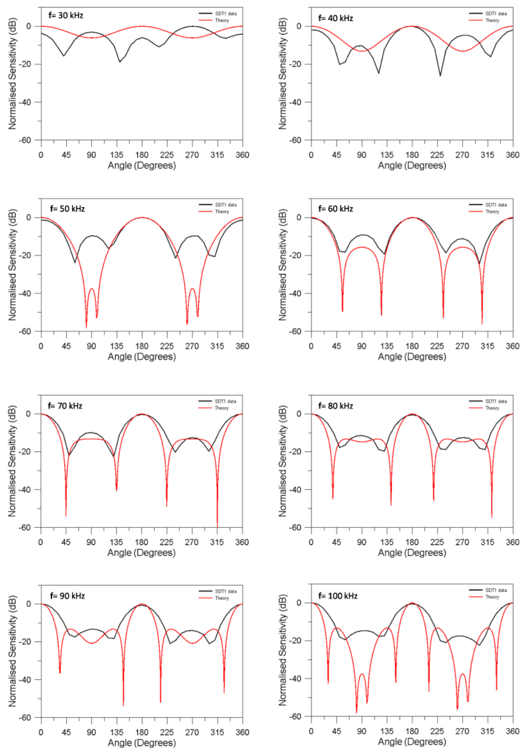

Figure 6. Normalized directivity plots for the SDT1 rectangular sensor (black) and theoretical directivity using equation 6.

CONCLUSION

In the frequency range 30 kHz< f < 100 kHz it was not possible to fit the measured sensitivities, at normal incidence by modelling the PVDF in thickness or hydrostatic expansion mode. The difference was as large as 21dB for the thickness mode and 17 dB for hydrostatic mode.

While an aperture function model successfully modelled the directionality at various frequencies for both the Airmar and SDT1 films, it was unable to do this for more than a few individual frequencies. The positions of the minima in the directionality plots show very little frequency dependence in the experimental data. This indicates that a piston in a rigid baffle model is not suitable for calculating the directionality of our PVDF sensors.

Use of a finte element model (PAFEC) gave good agreement with experiment over a large percentage of the frequency range. Futher work is required to optimise the polyurethane parameters shown in Table 3.

The polyurethane does not appear to attenuate the sensitivity of the sensor as would be expected. The cylindrical sensor which surrounds the SDT1 element with significantly more polyurethane than the rectangular sensor was 4 dB more sensitive than the thin rectangular sensor at normal incidence over the entire frequency range. This may well be due to the fact the acoustic impedences of the PVDF and polyurethane are quite similar. As a result the sensitivity of the film is more dependent on the surrounding polyurethane than would be the case of a ceramic element.

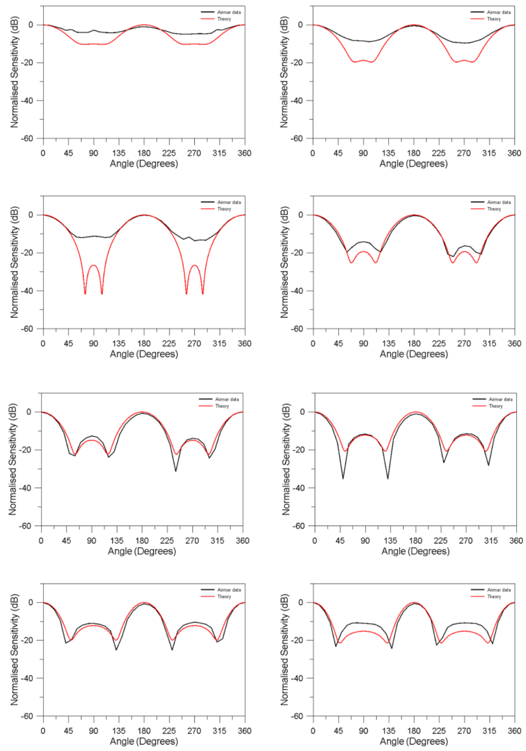

Figure 7. Normalized directivity plots for the Airmar rectangular sensor (black) and theoretical directivity using PAFEC

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